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# General equilibrium analysis of energy-saving and low-carbonized development for coal utilization in China

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**Abstract**

This study analyzes the effects of technological progress for coal utilization during urbanization in China by a hybrid computable general equilibrium model. Firstly, the impacts of energy efficiency and industrial technology upgrading on total coal consumption, coal consumption per unit of GDP and related carbon dioxide emissions per unit of GDP, electricity and heat consumption, electricity and heat consumption intensity during the period from 2002 to 2030 are examined. Then the effects of low-carbonized technology such as oxy-fuel combustion based CCS technology in coal-fired power industry are also estimated. Simulation results show that developing high-efficient and low-carbonized coal combustion technologies is the key to realize sustainable coal utilization in China.



*Keywords*: coal consumption; carbon dioxide; CCS technology; energy efficiency; CGE model

## 1. Introduction

Energy-saving has become national strategy which has been concerned unprecedentedly by Chinese government. For the planning of the 12th-five-year-plan period (2011-2015), a new target for energy efficiency and emissions abatement is set, which formulated that energy intensity should be reduced by 16% while carbon dioxide emissions per unit of GDP should be reduced by 17%. Since energy intensity has been reduced by 19.06% during the 11$^{th}$-five-year-plan period with huge investment and compulsory measures (e.g., power cut and production limit), further improvement of energy efficiency seems more difficult and complex in current China. Generally speaking, to reach the new energy-saving target for the 12$^{th}$-five-year-plan period is still a challenging task. In addition, Chinese national mid-term planning target requires that $CO_2$ emissions per unit of GDP should be reduced by 40%～45% from 2005 to 2020. Under such circumstances, energy-saving has been regarded as convenient and cheap method for energy

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security and $CO_2$ mitigation in China[1-3]. However, $CO_2$ mitigation only by improving energy efficiency seems not enough, low-carbonized technology also should be introduced into Chinese economy[4].

Because of unique characteristics about resource endowment and economic level in China, coal will still dominate Chinese primary energy consumption for a long time. Sustainable coal utilization appears extremely important to overall achievement of energy-saving & $CO_2$ mitigation in China. Excluding technological progress, coal consumption will be affected by other economic factors, such as energy substitution, economic growth and economic structure changing. Since computable general equilibrium model (i.e., CGE model) has classical and comprehensive macroeconomic framework which incorporates input-output theory with mathematic optimization method. Therefore this study will focus on analyzing the effects of technological progress for coal consumption and related $CO_2$ emissions in China by extending a computable general equilibrium model (i.e., CGE model). In addition, the impacts of introducing low-carbonized technology into coal-fired power industry are also analyzed.

## 2. Model

In this study, we constructs a hybrid CGE model, by extending a Chinese CGE model to hybrid energy CGE model[2]. Our hybrid energy CGE model includes the energy balance sub-model, the coal-fired power engineering sub-model and standard CGE model. Each sector's energy demand and energy production calculated by the CGE model are input into the energy balance model. From the energy balance model, we can calculate coal consumption amount in each energy utilization process. After coal consumption amount by coal-fired power generation has been estimated, the effects of introducing low-carbonized technology into coal-fired power industry can be simulated by the coal-fired power engineering sub-model.

### *2.1. Assumptions*

There are two kinds of household as rural type and urban type. Markets of commodity, labor and capital are perfectly competitive. The simulation period is 28 years interval of year 2002 to 2030. Chinese economy is divided into 22 industries. Assumptions about the population and the urbanization rates are set according to government predictions. The population in year 2010, 2020, and 2030 are estimated to be 1368 million, 1445million and 1470 million. The urbanization rates in year 2010, 2020, and 2030 are estimated to be 49%, 58% and 63%.

### *2.2. Parameter Setting*

About modeling the uncertainty of economic growth, utility discounted rate is setting as fixed value, which is 5%; while income discounted rate is setting as fluctuating value, which is ranged from 9.17% to 2.68% during the entire simulation period. In 2002, energy efficiency in China was about 30% lower than international advanced level.

### *2.3. Main Framework*

In this study, we employ a Chinese CGE model, driven by endogenous accumulation of capital[5-7]. Technological progress over time is exogenously given by the AEEI parameters and increasing rate of technological progress coefficients. Energy indicators are connected with CGE model by a transformation matrix. Energy use related carbon dioxide emissions are calculated according to each fuel's emissions factor, non-carbon used share and oxygen releasing rate. The fuels considered in this model are coal, crude oil, natural gas, coke, fuel oil, gasoline, kerosene, diesel, liquefied petroleum gas, refinery gas, coke oven gas and other coal gas. This model uses a combination of Leontief and Cobb-Douglas production structure. The model has fully flexible coefficients in the demand function of production and consumption. Under given commodity demand and price, behavior of industrial sectors can be described by cost minimization problem. The utility function is specified as a Cobb-Douglas type of composite consumption which is composed of composite rural consumption and composite urban consumption. Changing of urbanization rate directly affects final consumption structure, and the production structure is revised endogenously. Thus the energy substitution among traditional fossil fuels can be modified. The representative household consumes composite goods so as to maximize the integration of discounted subutility function over time. Then these composite goods are divided into 22 types of commodities maximizing a subutility function. The subutility function can be calculated by composite consumption by sector. The budget constraint imposed on the household is disposable income.

Above CGE model, energy balance sub-model and coal-fired power engineering sub-model are softly linked with each other. With the assumptions of technological progress about coal-fired power units are given exogenously, we can forecast emissions and assess technology for coal-fired power industry.

The basic structure of our model is shown as figure 1.

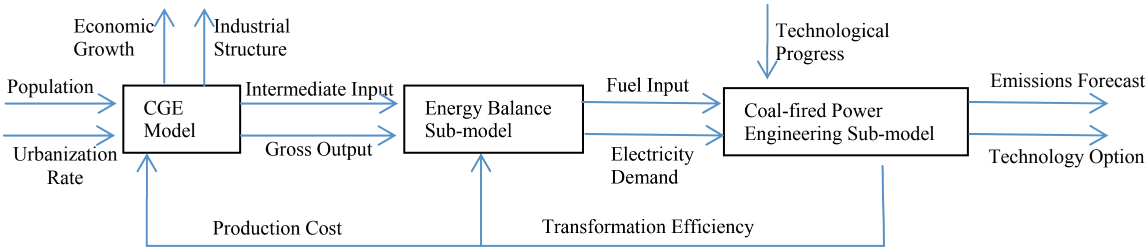



Fig. 1. The Basic Structure of the hybrid CGE Model

## 3. Results and Discussions

Assumptions of technological progress among agriculture sector, energy-intensive industrial sectors and non energy-intensive industrial sectors in five scenarios from 2002 to 2030 are given as table 1. The scenario 1 is business as usual, while other four scenarios have been assumed with a promotion of technological progress for energy-saving in industrial sectors. Since this model is based on 2002 input-output table, the GDP is calculated at 2002 comparable price in this paper.

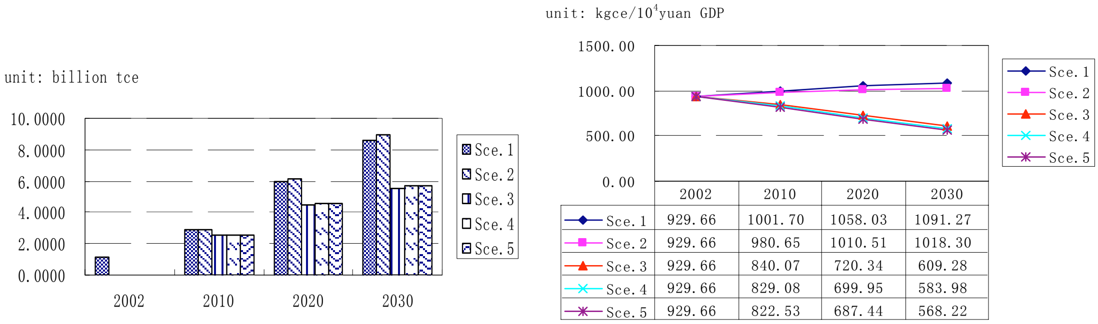
Table 1. Assumptions of energy-saving related technological progress

| | AEEI | Technological Progress Coefficiency | | |
|---|---|---|---|---|
| | | Energy-intensive sector | Non Energy-intensive Secor | Agriculture Sector |
| Sce.1 | 0 | 0 | 0 | 0 |
| Sce.2 | 0 | 10% | 15% | 0 |
| Sce.3 | 30% | 10% | 15% | 0 |
| Sce.4 | 30% | 15% | 20% | 0 |
| Sce.5 | 30% | 20% | 20% | 0 |

### *3.1. Total Coal Consumption*

The total coal consumption in above five scenarios is depicted as figure 2(a). In 2030, coal consumption can reach 8.60 trillion tce in scenario 1, 8.97 trillion tce in scenario 2, 5.57 trillion tce in scenario 3, 5.70 trillion tce in scenario 4 and 5.72 trillion tce in scenario 5. Compared with the level in 2002, coal consumption increases 660% in scenario 1, 692% in scenario 2, 392% in scenario 3, 403% in scenario 4 and 405% in scenario 5. The growth trend of coal consumption is similar with total energy consumption, but the growth speed becomes slower.

Coal consumption per unit of GDP (i.e., coal consumption intensity) in above five scenarios is depicted as figure 2(b). The changing process of coal consumption intensity is entirely similar with total energy intensity. It seems that energy efficiency improvement is more effective to reduce coal consumption intensity compared with higher value added rate. In scenario 1 and scenario 2 with no energy efficiency improvement, coal consumption intensity shows increasing. However, it is reduced by 34.46%, 37.18% and 38.88% in scenario 3, scenario 4 and scenario 5 from 2002 to 2030, which are reduced more than total energy intensity. The reason is coal will be gradually substituted by other clean and low-carbonized energy with the development of Chinese urbanization and industrialization, and the composition of coal consumption among total energy consumption will be dropping. Compared with higher value added rate, energy efficiency improvement is more effective to reduce coal consumption intensity. In scenario 1 and scenario 2 with no energy efficiency improvement, coal consumption intensity shows increasing. However, it is reduced by 34.46%, 37.18% and 38.88% in scenario 3, scenario 4 and scenario 5 from 2002 to 2030.



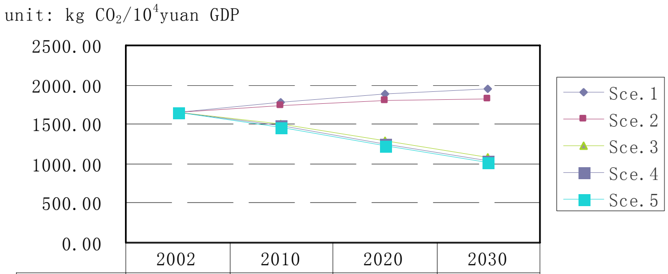

| | 2002 | 2010 | 2020 | 2030 |
|---|---|---|---|---|
| Sce.1 | 929.66 | 1001.70 | 1058.03 | 1091.27 |
| Sce.2 | 929.66 | 980.65 | 1010.51 | 1018.30 |
| Sce.3 | 929.66 | 840.07 | 720.34 | 609.28 |
| Sce.4 | 929.66 | 829.08 | 699.95 | 583.98 |
| Sce.5 | 929.66 | 822.53 | 687.44 | 568.22 |

Fig. 2. (a) total coal consumption; (b) coal consumption intensity

### *3.2. Coal consumption related $CO_2$ emissions per unit of GDP*

Carbon dioxide emissions per unit of GDP by coal consumption in above five scenarios are depicted as figure 3.

From Figure 3, we can find the changing extent of carbon dioxide emissions per unit of GDP by coal consumption is entirely same with coal consumption intensity in each scenario. But compared with carbon dioxide emissions per unit of GDP by total energy consumption, in scenario 1 and scenario 2 they are increased less. However, in scenario 3, scenario 4 and scenario 5 they are reduced more than that by total energy consumption. Such phenomenon is caused by energy substitution. Since coal will be substituted more and more by other clean, low-carbonized energy during the urbanization in China, in each time interval we can find that the share of carbon dioxide emissions by coal consumption among will become less among carbon dioxide emissions by total energy consumption.

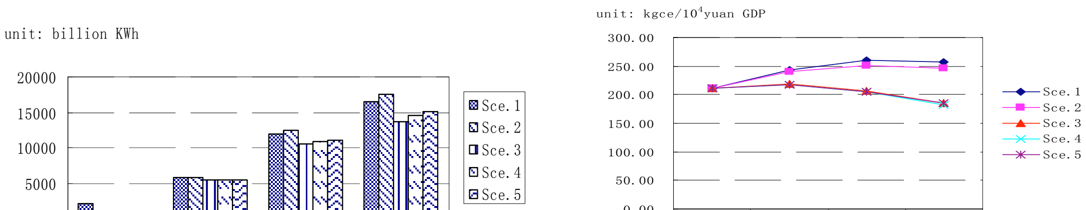



| | 2002 | 2010 | 2020 | 2030 |
|---|---|---|---|---|
| Sce. 1 | 1656.53 | 1784.90 | 1885.28 | 1944.50 |
| Sce. 2 | 1656.53 | 1747.39 | 1800.60 | 1814.48 |
| Sce. 3 | 1656.53 | 1496.90 | 1283.55 | 1085.66 |
| Sce. 4 | 1656.53 | 1477.32 | 1247.21 | 1040.57 |
| Sce. 5 | 1656.53 | 1465.64 | 1224.93 | 1012.49 |

Fig. 3. coal consumption related $CO_2$ emissions per unit of GDP

### 3.3. Electricity and heat consumption

The total electricity and heat consumption in above five scenarios is depicted as figure 4(a), while electricity and heat consumption intensity is depicted as figure 4(b).




| | 2002 | 2010 | 2020 | 2030 |
|---|---|---|---|---|
| Sce. 1 | 210.65 | 243.76 | 259.46 | 257.22 |
| Sce. 2 | 210.65 | 240.30 | 251.78 | 245.89 |
| Sce. 3 | 210.65 | 218.59 | 207.10 | 184.99 |
| Sce. 4 | 210.65 | 217.25 | 204.94 | 182.71 |
| Sce. 5 | 210.65 | 217.48 | 205.83 | 184.47 |

Fig. 4. (a) total electricity and heat consumption; (b) electricity and heat consumption intensity.

Compared with the level in 2002, electricity and heat consumption increases 690% in scenario 1, 744% in scenario 2, 559% in scenario 3, 595% in scenario 4 and 624% in scenario 5. The growth speed of electricity and heat consumption is greater than coal consumption in these scenarios. In scenario 3, scenario 4 and scenario 5, it is even larger than total energy consumption. Since electricity and heat is super clean, it is reasonable that the growth of electricity and heat consumption will become faster than coal consumption. Therefore, electricity and heat production sector will still develop in large scale in the future. For the case of electricity and heat consumption intensity, the situation is a little different. During the first period from 2002 to 2010, electricity and heat consumption intensity shows increasing in above five scenarios. During the period from 2011 to 2030, electricity and heat consumption intensity can only be reduced by 15.37%, 15.90% and 15.18% in scenario 3, scenario 4 and scenario 5. Compared with scenario 4, higher value added rate of energy intensive industries in scenario 5 means such industries have higher growth rate, economic structure turns heavier, and consumption of electricity and heat becomes increasing. It directly makes electricity and heat consumption intensity in scenario 5 depict higher than that in scenario 4. Electricity and heat consumption intensity seems more difficult to be reduced compared with coal. Generally speaking, saving electricity and heat in each social sector should be strictly implemented at first.

### *3.4. Coal-fired power industry*

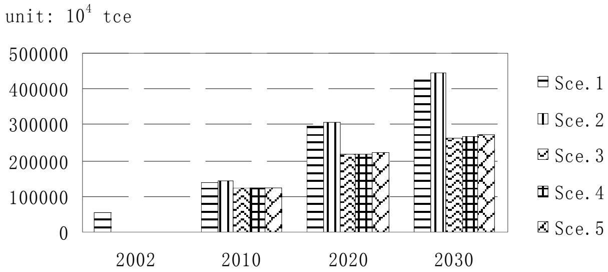
Over 70 percent of total electricity in China is generated from coal-fired power units, and this situation will still last in the long future. Moreover, coal-fired power industry has become the largest CO2 emitter among Chinese industrial sectors, and the $CO_2$ emissions from coal-fired power plants in China account for nearly 40% of the national total emissions amount. In this sector, we try to study how will coal-fired power industry in China realize low-carbonized development.

Firstly, we forecast the proportion of coal-fired power generation among total electricity & heat production and the proportion of power generation related coal consumption among total coal consumption from 2002 to 2030, and the results are shown as table 2. The proportion of coal-fired power generation appears little decreasing from 2002. In the scenarios with no energy efficiency improvement (i.e., Sce.1 and Sce.2), the price of coal-fired power generation becomes higher than other scenarios, and then the proportion of coal-fired power generation shows lower. But the dropping speed of this proportion in all these five scenarios seems very slow. In scenario 3, scenario 4 and scenario 5, this proportion is even still larger than 70% in 2030. In addition, the proportion of power generation related coal consumption among total coal consumption always remains very high from 2002 to 2030. This proportion seems especially high in 2020. The reason is that industrial structure tends to less coal dependent during Chinese urbanization, while electricity industry still remains coal dependent. Owing to abundant coal resource, it can be imagined that coal-fired power units will remain high proportion in electricity production for a long time in China. Therefore, the proportion of coal-fired power generation as shown in table 2 is reasonable and acceptable.

Table 2. Proportion of coal-fired power generation among total electricity & heat production and proportion of coal consumption by power generation among total coal consumption (unit: %)

| | Proportion of power generation | | | | | Proportion of coal consumption | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sce.1 | Sce.2 | Sce.3 | Sce.4 | Sce.5 | Sce.1 | Sce.2 | Sce.3 | Sce.4 | Sce.5 |
| 2002 | 82.3 | 82.3 | 82.3 | 82.3 | 82.3 | 46.0 | 46.0 | 46.0 | 46.0 | 46.0 |
| 2010 | 66.3 | 65.9 | 79.1 | 78.5 | 77.8 | 48.9 | 48.9 | 48.1 | 48.1 | 48.1 |
| 2020 | 67.3 | 66.3 | 81.5 | 80.1 | 78.4 | 50.0 | 50.1 | 48.4 | 48.4 | 48.5 |
| 2030 | 69.3 | 67.9 | 79.5 | 77.3 | 74.6 | 49.5 | 49.7 | 47.2 | 47.2 | 47.3 |

The coal consumption by coal-fired power generation is depicted as figure 5(a), and related $CO_2$ emissions in above five scenarios are depicted as figure 5(b). We can find that during the first period from 2002 to 2010, coal consumption and its related $CO_2$ emissions by coal-fired power generation appear very fast increasing trend. In this period, coal consumption and related $CO_2$ emissions increase 171%, 173%, 133%, 134% and 134% in these five scenarios respectively. During the period from 2011 to 2020, the increasing speed becomes slower than first period, and coal consumption and related $CO_2$ emissions increase 111%, 115%, 79%, 80% and 81% in these five scenarios respectively. During the period from 2021 to 2030, the increasing speed of coal consumption and related $CO_2$ emissions by coal-fired power generation appears slower even than first period, and coal consumption and related $CO_2$ emissions increase 43%, 46%, 22%, 23% and 24% in all these five scenarios respectively. Obviously, with higher speed of economic growth and urbanization in first period, coal consumption and related $CO_2$ emissions by coal-fired power generation are increased fastest. In second period and third period, the increasing speed of coal consumption and related $CO_2$ emissions by coal-fired power generation become slower, but their increasing extent still seems very large. In order to reduce the increasing extent of coal consumption, energy-saving related technological progress should be promoted in coal-fired power industry. In fact, with powerful energy efficiency improvement in scenario 3, scenario 4 and scenario 5, the coal consumption and related $CO_2$ emissions can be greatly reduced. Therefore, energy-saving should be regarded as prior development strategy by coal-fired power industry.



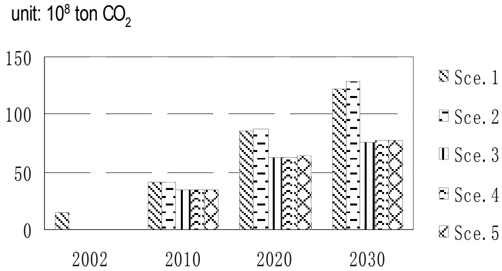




Fig. 5. (a) coal consumption by coal-fired power generation; (b)$CO_2$ emissions by coal-fired power generation

However, even with powerful energy efficiency improvement (i.e., sce.3, sce.4 and sce.5), $CO_2$ emissions from coal-fired power industry have been close to 8 billion ton in year 2030. Obviously, abatement of $CO_2$ emissions by energy-saving in coal-fired power industry is not enough, low-carbonized technology should be introduced into this industrial sector in mid-long term. Carbon capture and storage (i.e., CCS) is a means of capturing $CO_2$ which is produced by the use of fossil fuel and storing it in geological framework or the ocean safely thus sequestrate $CO_2$ from the atmosphere. Even until now, over 70% of Chinese electricity generation is still produced by coal-fired power units. Undoubtedly, $CO_2$ emissions from coal-fired power industry in China will rapidly increase by 2050. From view of long term, CCS will be the fundamental technology option for China's electricity industry to deal with the large-scale $CO_2$ emissions.

Table 3. Techno-economic parameters of CCS Technology in typical oxy-fuel combustion plants

| | Generation Efficiency (%) | Generation Cost (Yuan/MWh) | $CO_2$ Emissions (kg/KWh) |
|---|---|---|---|
| Technology 1 (Ultra-supercritical units in oxy-fuel combustion plants) | 39.2 | 82.3 | 82.3 |
| Technology 2 (Ultra-supercritical units in normal plants with $deNO_x$ and $deSO_2$) | 44.0 | 65.9 | 79.1 |
| Technology 3 (Supercritical units in oxy-fuel combustion plants) | 36.0 | 66.3 | 81.5 |
| Technology 4 (Supercritical units in normal plants with $deNO_x$ and $deSO_2$) | 40.5 | | |
| Technology 5 (Subcritical units in oxy-fuel combustion plants) | 34.2 | | |
| Technology 6 (Subcritical units in normal plants with $deNO_x$ and $deSO_2$) | 38.4 | 67.9 | 79.5 |

Note: Above data are estimated according to the references [8-9]

There are mainly three carbon capture technologies for coal-fired power plants: post-combustion capture, pre-combustion capture (IGCC) and oxy-fuel combustion. The post-combustion capture technologies, such as rectification, physical adsorption, chemical adsorption and separation membrane have problems of scale limitation and high cost generally. Although high overall economic efficiency is performed by the pre-combustion capture technique based on IGCC (IGCC-CCS), it is hard to be applied in large-scale. Also, it has great difficulties to combine with the large numbers of domestic coal-fired power plants as well as those power plants under-construction due to the complication of the system and technique. On the contrary, oxy-fuel combustion technique can be applied in the mainstream techniques of existing power plants and it is suitable for the transformation of the existing power units and the ones under-construction. The oxy-fuel combustion technique can be also easily implemented in technique with a relatively low overall cost.

Oxy-fuel combustion technology has been well investigated and developed in recent years. In August 2010, U.S. Government carried out the technical route of FutureGen Programs and announced that there will be some major adjustments, which turn the step of capture before combustion in the original plan to oxy-fuel combustion. And the world's first set of the whole process 200 MW carbon capture and storage demonstration project will be built by 2015. It is believed that oxy-fuel combustion is likely to be the lowest cost option for clean utilization of the existing fossil power plants and storing $CO_2$ by geographic sequestration. Some main technical parameters of CCS technology in typical oxy-fuel combustion plants are depicted as table 3.

Most of the new installed coal-fired power units are supercritical or ultra-supercritical units which have high function parameters and high capacities. By far, China has the largest number of 1000 MW ultra-supercritical units in the world including thirty-three installed and eleven under construction. Therefore, CCS technology will be combined with supercritical or ultra-supercritical in the future. In our model, we assume that CCS technology based on oxy-fuel combustion system will be introduced in coal-fired power industry after 2020, and the proportion of electricity generated by power units equipped with CCS facility in oxy-fuel combustion plants will reach 5% among total coal-fired power generation in 2030. Among this 5% proportion, there are 2% electricity generated by subcritical units in oxy-fuel combustion plants, other 2% and 1% electricity generated by supercritical units and ultra-supercritical units in oxy-fuel combustion plants respectively. In addition, scenario setting about the generation mix of condensing coal-fired power units in 2030 China and related simulation results are shown as table 4.

Table 4. Scenario setting about generation proportion of CCS units in coal-fired power industry and related simulation results

| | Generation proportion of CCS units (%) | | | Additional coal cosumption | Abatement amount of $CO_2$ emissions ($10^8$ ton $CO_2$) |
|---|---|---|---|---|---|
| | Tech1 | Tech 2 | Tech 3 | ($10^4$ tce) | |
| Sce.1 | 0 | 0 | 0 | 0 | 0 |
| Sce.2 | 0 | 0 | 1 | 559.64 | 0.93 |
| Sce.3 | 0 | 1 | 2 | 1274.94 | 2.51 |
| Sce.4 | 1 | 2 | 2 | 2079.06 | 4.16 |
| Sce.5 | 2 | 3 | 3 | 3328.35 | 6.66 |

According to table 4, with CCS technology introduced into coal-fired power industry in 2030 China, we still need 5.5964, 12.7494, 20.7906 and 33.2835 million tce additional coal consumption in scenario 2, scenario 3, scenario 4 and scenario 5. This means coal consumption by whole coal-fired power industry will increase 0.13%, 0.49%, 0.77% and 1.23% respectively in above scenarios. In addition, 0.093, 0.251, 0.416 and 0.666 billion ton $CO_2$ emissions can be abated in scenario 2, scenario 3, scenario 4 and scenario 5. This means $CO_2$ emissions by whole coal-fired power industry will decrease 0.73%, 3.32%, 5.38% and 8.56% respectively in above scenarios. We can see that more proportion of $CO_2$ emissions can be abated with less proportion of additional coal consumption. The additional coal consumption per billion ton $CO_2$ emissions abatement is 60.164, 50.803, 49.926 and 49.947 million tce respectively in scenario 2, scenario 3, scenario 4 and scenario 5. It seems that with more shares of supercritical units and ultra-supercritical units installed with CCS facilities, the additional coal consumption by CCS technology will be reduced.

## 4. Conclusion

Based on above analysis, high-efficient and low-carbonized coal utilization is crucial for the overall effects of energy-saving and emissions abatement in current China. Obviously, through promoting energy-saving related technological progress, effective reduction of coal consumption intensity can be implemented in the process of Chinese urbanization. However, the total $CO_2$ emissions induced by coal consumption will still continue to be rapidly increasing if only through energy efficiency improvement. From the long-term view, oxy-fuel combustion based CCS technology should be developed for changing the rapid increasing trend of coal consumption related $CO_2$ emissions in China. In order to minimize additional coal consumption for operation of CCS facilities, oxy-fuel combustion based CCS technology could be considered to be developed by combining with high parameter and large capacity units, such as supercritical or ultra-supercritical coal-fired power units.

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